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A review on wind energy and wind–hydrogen production in Turkey: A case study of hydrogen production via electrolysis system supplied by wind energy conversion system in Central Anatolian Turkey

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A B S T R A C T

Studies about investigation of hydrogen production from wind energy and hydrogen production costs for a specific region were reviewed in this study and it was shown that these studies were rare in the world, especially in Turkey. Therefore, the costs of hydrogen, hydrogen production quantities using a wind energy conversion system were considered as a case study for 5 different locations of Nigde, Kirsehir, Develi, Sinop and Pinarbasi located in the Central Anatolia in Turkey. Annual wind energy productions and costs for different wind energy conversion systems were calculated for 50 m, 80 m and 100 m hub heights. According to wind energy costs calculations, the amounts and costs of hydrogen production were computed. Furthermore, three different scenarios were taken into account to produce much hydrogen. The results showed that the hydrogen production using a wind energy conversion system with 1300 kW rated power had a range from 1665.24 kgH_2/year in Nigde at 50 m hub height to 6288.59 kgH_2/year in Pinarbasi at 100 m hub height. Consequently, Pinarbasi and Sinop have remarkable wind potential and potential of hydrogen production using a wind–electrolyzer energy system.

Contents

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Nomenclature

a	regression constant
C_{bb}	battery bank cost ($)
C_{ci}	civil works cost ($)
C_{EACC}	annual capital cost of electrolyzer ($/year)
C_{EE}	cost of energy from wind turbine ($/kWh)
C_{EXP}	cost of energy exported to grid ($/kWh)
C_f	capacity factor
C_{H_2}	hydrogen production cost ($/kg)
C_{in}	inverter cost ($)
C_{misc}	miscellaneous equipments costs ($)
$C_{O,M}$	operation and maintenance costs ($)
$C_{OM\text{-}EE}$	operation and maintenance cost for electrolyzer ($)
$C_{om\text{-}esc}$	operation and maintenance cost for wind turbine ($)
CRF	capital recovery factor
C_w	total investment cost of the wind energy system ($/kWh)
C_{wt}	wind turbine cost ($)
E_{EX}	excess energy (kWh/year)
E_{EXC}	excess energy from the electrolyzer (kWh)
e_{om}	operation and maintenance escalation ratio (%)
E_p	annual produced energy from wind turbine (kWh/year)
E_R	annual rated power of wind turbine (kWh)
I_w	specific cost of the wind energy system ($/kWh)
LCE	levelized cost of electricity ($/kWh)
m_{H_2}	annual amount of produced hydrogen from electrolyzer (kg/year)
n	useful life of the system (year)
P_R	rated power of the wind turbine ($)
PR_{EXP}	profit from energy exported to grid ($/year)
r	discount rate (%)
v	wind speed (m/s)
v_0	measured wind speed (m/s)
V_{ci}	cut-in speed (m/s)
V_{co}	cut-out speed (m/s)
V_R	rated wind speed (m/s)
z	desired height (m)
z_0	measurement height (m)
z_s	surface roughness

1. Review of wind energy studies in Turkey

The term of "renewable energy" has become more popular all over the world. The world has to find new energy sources due to harmful effects of the fossil fuels to the atmosphere and their limited quantities. Wind energy as a renewable energy has developed more quickly than the other renewable energy sources. In Turkey, a lot of studies on the estimation of wind characteristics and calculation of wind energy cost were investigated. Ilkilic and Turkbay [1] evaluated the wind potential of Turkey. They calculated the annual average wind speed of each region of Turkey, and concluded that Turkey had annual mean wind speed of 2.58 m/s and had annual average wind density of 25.82 W/m^2. Ilkilic and Nursoy [2] investigated wind power density and mean wind speed at different locations in Turkey. They mentioned that the electricity which could be obtained from wind was 10 GW potential. Furthermore, they concluded that wind turbine can be installed at several locations in Turkey. Erdogdu [3] presented the wind energy potential in Turkey and compared with the wind potential of European OECD countries. It was showed that Turkey had the greatest potential among those countries with 83,000 MW technical wind energy potential. Moreover, in the studies of Ogulata [4], Kaygusuz [5], Evrendilek and Ertekin [6] and Ozgur [7], the wind power usage was compared with the other renewable energy sources in Turkey.

Akdag and Dinler [8] used a new method called power density (PD) method to obtain Weibull distribution. In order to validate this method, different studies performed in Maden, Gokceada, Canakkale, and Bozcaada in Turkey. It was concluded that the new method was more suitable than the other methods such as Maximum Likelihood, Moment and Graphic methods. Furthermore, Akdag and Guler [9] carried out the evaluation of wind energy investment and costs of wind energy in Turkey. They estimated the production of energy from wind energy conversion systems (WECS) and capacity factors of WECSs as being reached to 287 TWh and 41.9% with new wind license applications. In addition, they presented the studies of Marmara, Aegean, Mediterranean, Eastern Anatolia and South Eastern Anatolia regions. They made an economic analysis for some locations in Turkey and found that the cost was between 1.73 and 4.99 $cent/kWh. Guler [10] and Kaygusuz [11] emphasized that although Turkey had the highest wind potential in Europe countries, Turkey had the lowest usage ratio of wind energy. According to this investigation on the technical potential of wind energy of Turkey was 88,000 MW, the installed wind capacity was only 21.84 MW. Similarly, Alboyaci and Dursun [12] discussed the situation of wind energy in Turkey. They researched the wind potentials of the European countries, wind capacities of the some countries around the world. They mentioned that the Europe had the biggest share of wind power usage as 73%.

Karsli and Gecit [13] determined the wind power potential of the Nurdagi/Gaziantep district. They resulted that the mean wind speed and wind power density of Nurdagi was 7.3 m/s and 222 W/m^2, respectively. Celik [14] made a study about techno-economic analysis of wind energy for Southern Turkey. In the study he analyzed the variation of costs by using life-cycle cost analysis approach for different rated power wind turbines. As a result, he reported that the lowest cost of electricity was 0.15 $/kWh for 500 kW wind turbine. Sahin and Bilgili [15] investigated the wind characteristics of Belen-Hatay province in southern Turkey by using Wind Atlas Analysis and Application Program (WAsP). According the results, they determined that the mean wind speed was 7 m/s and power density was 378 W/m^2 at 10 m height above ground level. Bilgili and Sahin [16] studied to determine wind characteristics for Akhisar, Bababurnu, Gelibolu and Gökceada regions statistically by using WAsP program. As a result, they reported that these regions have remarkable wind potential but Gökceada and Gelibolu were the most suitable to build wind turbines. Akpinar and Akpinar [17] made a similar study to determine wind potential of the region of Maden-Elazig in eastern Turkey. They showed that the mean wind speed had a range of 5 and 6 m/s and Maden had annual mean power density of 244.65 W/m^2. Ozgener [18] determined the wind energy potential of the Celal Bayar University Muradiye Campus. In this study the wind speeds were obtained between 2006 and 2007 using an experimental system. Ozgener predicted that the installation of wind energy system would not be economical due to its low capacity factor of 14.1%. Kose [19] and Kose et al. [20] used Weibull and Rayleigh models to obtain wind potential of Kutahya, Dumlupinar University. It was pointed out that the results of Weibull model were better than Rayleigh model. Ozerdem and Turkeli [21] presented the wind characteristics such as wind

speed, turbulence intensity and wind direction for Izmir Institute of Technology campus. They concluded that the campus region had a high wind potential to utilize wind turbine systems. Furthermore, they selected the most suitable wind turbines as 600 kW and 1500 kW. Ozerdem et al. [22] carried out both technical and economic feasibility study for a wind farm in Izmir-Turkey using three diverse scenarios for economical evaluation. It was shown that the production cost per kWh and internal rate of return value for all three scenarios were reasonable. Kocatepe et al. [23] conducted an analysis of power quality of two different wind farms with capacity of 10.2 MW and 30 MW in Turkey. Wind farm with capacity of 10.2 MW was located at Bandirma, Balikesir and wind farm with capacity of 30 MW at Bozcaada, Canakkale. In this study; flicker, harmonics and power quality of wind plants were investigated, this investigation was resulted that wind plants had negative impacts on the medium level of transmission network. Mutlu et al. [24] carried out to analyze power quality of a wind farm in Alacati, Turkey. In order to evaluate the power quality of wind farm, they used in a machine drive system in laboratory and they implemented the same model to a wind farm which had 12 turbines in Alacati substation. Eskin et al. [25] investigated the wind potential of Gokceada Island in Turkey. They used wind data of different locations (Ugurlu, Cinaralti, Aydincik and National Weather Station) to estimate the wind potential of the region. They calculated the Weibull parameters for each location to obtain wind density of the region. This study pointed out that Gokceada Island had high wind speeds and wind power to install wind turbine system. Ucar and Balo [26] estimated wind potential of Uludag in Turkey. They used Weibull and Rayleigh probability functions to obtain wind speed distribution of the region. They performed an economic analysis to find costs of wind energy systems. It was resulted that the mean wind speed was 7.08 m/s in the region and the costs changed between 0.255 and 0.306 $/kWh. Ucar and Balo [27] investigated the assess wind power potential in coastal areas of Turkey. They evaluated the annual mean wind speed and mean wind density of each region in Turkey. They calculated the capacity factor and energy output of different wind turbines such as 600 kW, 1.5 MW, 2 MW and 2.5 MW. Onat and Ersoz [28] studied wind potential of Samandag, Amasra and Guney in Turkey. They used the ANFIS model to estimate wind speeds of the regions. According to the results, it was concluded that the selected regions were suitable for usage of the wind power. Gokcek et al. [29,30] presented the wind energy potential of Kirklareli city in Turkey. The results pointed that the wind energy conversion system could be used more effectively with 2300 kW rated power wind turbine. Genç and Gokcek [31], and Gokcek and Genç [32] carried out the study of wind characteristics in Central Anatolia Turkey and their results showed that Pinarbasi had considerable wind potential. Furthermore, they presented that 121 MWh/year energy output could be obtained with the small scale wind turbine with 150 kW rated power at 30 m hub height, and the costs were between 0.29 $/kWh and 30 $/kWh. Genç [33] evaluated the annual wind energy output, capacity factor and wind energy production costs at different hub heights by using large-scale WECSs in Nigde, Develi, Sinop, Kirsehir and Pinarbasi located in Central Anatolia in Turkey. It was pointed out that Pinarbasi and Sinop regions between considered locations had remarkable wind potential and the wind energy cost of large-scale WECSs in Pinarbasi and Sinop were lower than and equal to the minimum selling price of electricity determined by Turkey Energy Market Regulatory Authority.

2. Review of wind–hydrogen energy studies

Researchers accept that hydrogen will become the future's energy carrier and the world will build again on a hydrogen economy. Because of that, hydrogen energy researches increase more and more in last two decades. Today, a large amount of hydrogen is produced from fossil fuels by using steam methane reforming (SMR) or coal gasification methods. Sovacool and Hirsh [34] mentioned that the idea of hydrogen production from wind turbines on the islands had many advantages. They presented that the demonstration systems on the Unst, Utsira and Lolland islands had great offer for energy costs. Khan and Iqbal [35] performed a study to modelization and simulation of a stand-alone wind–hydrogen energy system. They concluded that direct torque sensing wind turbine controller and low voltage-high current behavior of electrolyzer model could enhance the system. The study showed that the simulation was successful to obtain system dynamics. Rodriguez et al. [36] analyzed wind energy and hydrogen production potential, and costs of hydrogen production of Cordoba region in Argentina. They mentioned that produced hydrogen from electrolysis system could be used in automotive transportation in the region. The results presented that the hydrogen necessity in automotive transportation could be supplied ten times using the wind–hydrogen system. Furthermore, comparison of hydrogen and gasoline costs for the region showed that hydrogen costs could compete with conventional fuels. Mantz and Battista [37] investigated to produce hydrogen via excess energy from wind turbines. They analyzed the system configuration and developed a control strategy for the system. Honnery and Moriarty [38] estimated the global hydrogen production from wind energy. The global technical hydrogen production was obtained as 116 EJ by placing one 2 MW wind turbine/km^2 over the surface of the earth. Hamane et al. [39] carried out a feasibility study to produce hydrogen from wind power in Ghardaia region. The results showed that 3200 N m^3 of hydrogen obtained at 30 m hub height and 4200 N m^3 of hydrogen obtained at 60 m. Bernal and Lopez [40] presented a technical-economic analysis of a wind–hydrogen system. They mentioned that the prices of the hydrogen components were very high and energy generation by the fuel cell was 171 c€/kWh. Korpas and Greiner [41] evaluated the performance of wind–hydrogen energy systems and described the benefits of the hydrogen as a controllable load in wind energy conversion system and the backup of hydrogen to the grid usage and hydrogen storage size. Mathur et al. [42] investigated the economics of the hydrogen production as transportation fuel in offshore wind energy systems. The results showed that hydrogen production costs could not compete with petrol prices using offshore wind systems, however hydrogen had good expectances to transition hydrogen economy. Jorgensen and Ropenus [43] studied on the hydrogen production prices from grid-connected electrolyzers with different wind penetration scenarios and the calculations showed that prices had a range from 0.41 €/N m^3 to 0.45 €/N m^3. Greiner et al. [44] presented a method to evaluate the hydrogen production from wind power requiring chronological and economic computations. The results of this method pointed out that the hydrogen costs were between 2.8 €/kg and 6.2 €/kg. Gokcek [45] investigated the annual electrical energy from wind and hydrogen production potential in Kirklareli, Turkey. Furthermore, it was calculated the costs of hydrogen production for different hub heights. The study presented that the annual hydrogen production was 102.37 kg/year, annual electrical energy production was 15,148.26 kWh/year and the hydrogen production costs were between 0.3485 $/kg and 4.4898 $/kg. Genç et al. [46] evaluated a wind–electrolyzer–fuel cell system to supply energy demand of a chicken farm. It was taken into account that basic electrical devices used in the chicken farm were fans for air conditioning, lamps for lightening and feed handling equipments. The system included an electrolyzer, a fuel cell and a wind turbine, and it was assumed that there was a compressor to deliver the produced hydrogen from electrolyzer to hydrogen storage tank, and a hydrogen tank to store hydrogen with high pressure, and a

converter for DC to AC or AC to DC conversion. In addition, PEM electrolyzer and PEM fuel cell system were chosen due to their remarkable operation conditions. This study showed that that the hydrogen production costs were highly related to electrolyzer nominal power, costs of electricity produced from turbine and turbine hub height. Olateju and Kumar [47] evaluated the hydrogen production by using 1.8 MW wind turbine in Western Canada. They calculated the hydrogen production costs of 10.15 $/kg$H_2$ and 7.55 $/kg$H_2$ from 240 kW and 360 kW electrolyzers, respectively.

Consequently, studies about investigation of hydrogen production from wind energy and hydrogen production costs for a specific region are rare in the world, especially in Turkey. Because of this deficiency, the costs of hydrogen, hydrogen production quantities using wind energy conversion system (WECS) were investigated for 5 different locations of Nigde, Kirsehir, Develi, Sinop and Pinarbasi located in the Central Anatolia in Turkey in this study. For each location, wind energy production was calculated with four different WECSs with 300 kW, 600 kW, 1300 kW and 2300 kW rated power at three different hub heights (50 m, 80 m and 100 m). Based on amount of wind energy productions, the costs and potentials of hydrogen production were found and the variation of hydrogen production and costs were presented using three scenarios by changing rated power of electrolyzers.

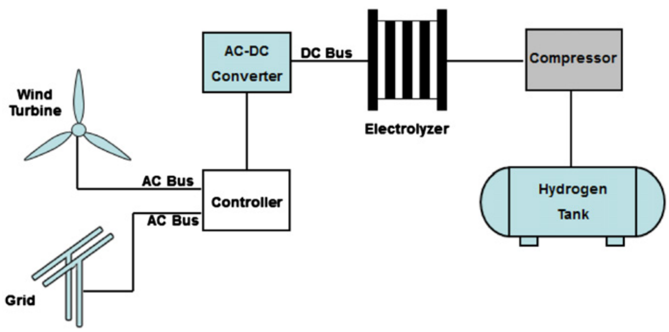

Fig. 1. System elements of the wind–electrolyzer energy system.

3. A case study: hydrogen production via electrolysis system supplied by wind energy conversion system in Central Anatolian Turkey

In this study, a wind–electrolyzer system was considered to produce hydrogen as a hydrogen production plant. As shown in Fig. 1, in the system, there is a wind turbine to produce electricity from wind and an electrolyzer unit to produce hydrogen from wind energy by using electrolysis methods. The electrolysis method is the easiest way to produce hydrogen. There are two common electrolyzer types: alkaline electrolyzers and PEM electrolyzers. In this study, the PEM electrolyzer was used because of its good ability of integration with renewable energy systems.

In the system, hydrogen production was made by splitting water via produced electricity from wind turbine. As shown in flowchart in Fig. 2, in this study, it was assumed that hydrogen production was occurred primarily, and excess energy was sold to the network to decrease hydrogen production costs.

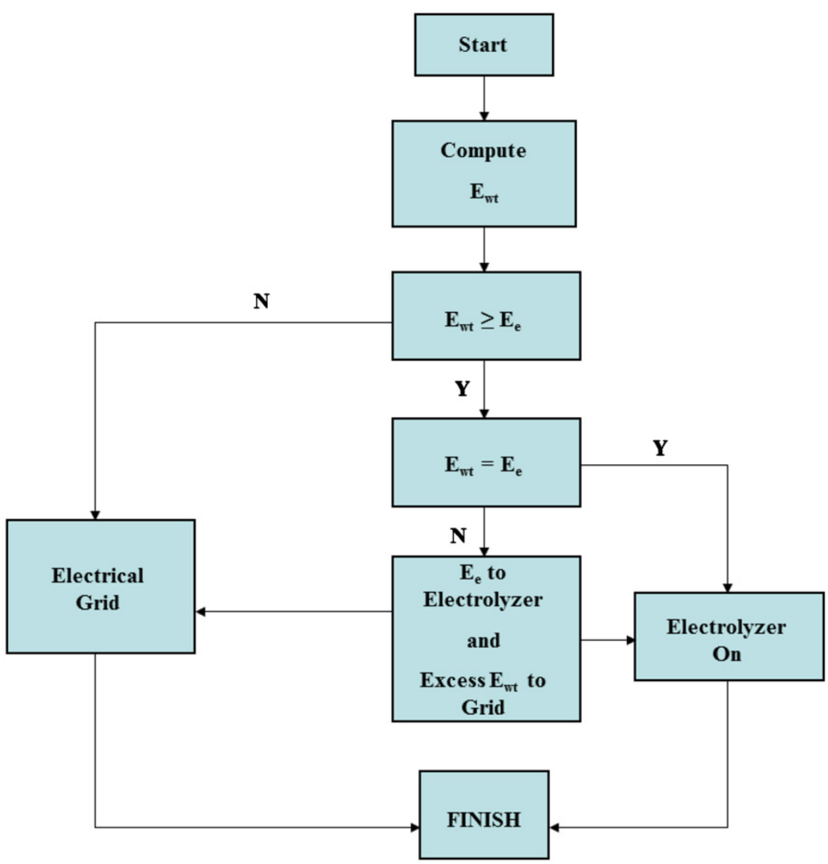

Fig. 2. Flowchart of the considered wind–electrolyzer system.

Table 1
Geographic location and wind characteristics of the considered sites at 10 m height on the ground [33].

Location	Latitude (N)	Longitude (E)	Altitude (m)	*v* (m/s)	*k*	*c* (m/s)
Pinarbasi	38°43′	36°24′	1500	3.67	1.49	4.09
Sinop	42°01′	35°10′	32	3.02	1.21	3.22
Kirsehir	39°09′	34°10′	1007	2.49	1.36	3.19
Nigde	37°58′	34°41′	1211	2.48	1.64	2.76
Develi	38°23′	35°30′	1180	2.60	1.88	2.97

Table 2
Surface roughness values for considered locations [33].

Station	Land use category	z_s	Wind speed at 50 m (m/s)
Pinarbas	Savannah	0.15	5.08
Sinop	Forest	0.5	4.64
Kirsehir	Mixed shrubland/grassland	0.3	3.63
Nigde	Mixed shrubland/grassland	0.3	3.62
Develi	Savannah	0.15	3.60

4. Wind speed in Central Anatolian Turkey

Wind potential, wind distribution parameters (shape factor and scale factor) and the mean velocity of the wind were determined by Genç and Gokcek [31], Gokcek and Genç [32] and Genç [48] for Pinarbasi, Sinop, Kirsehir, Nigde, Develi in Central Anatolia Turkey. In Table 1, geographic location, altitude, velocity of wind, shape and scale factors were given for considered locations of Pinarbasi, Sinop, Kirsehir, Nigde, Develi. Table 1 shows that Pinarbasi has the biggest altitude of 1500 m. Furthermore, the mean wind speed of Pinarbasi is 3.67 m/s and this value is greater than the other locations. It means the wind energy system can be used more effectively in Pinarbasi than in the other locations. The location of Sinop has the lowest altitude and it has minimum shape factor, k than the other locations.

In this study, three different hub heights (50 m, 80 m, 100 m) were considered for wind turbines. In order to use these parameters for 50 m, 80 m or 100 m hub height, the wind data extrapolate for those heights by using log law boundary layer profile expression [48].

$$v = v_0 \frac{\ln(z/z_s)}{\ln(z_0/z_s)} \tag{1}$$

where v, v_0, z, z_0, z_s determine wind speed, measured wind speed, desired height, measurement height and surface roughness, respectively. Surface roughness value depends on land characteristics such as savannah, forest, shrubland or grassland, and it was chosen from Table 2 [33]. It was obtained that Pinarbasi had the mean wind speed of 5.08 m/s and Sinop had the mean annual wind speed of 4.64 m/s at 50 m hub height as shown in Table 2. These obtained wind speeds correspond to the values on Turkish Wind Atlas for closed plains.

5. Wind energy conversion and electrolysis system

5.1. Wind energy conversion system

For four different WECSs were considered as 300 kW, 600 kW, 1300 kW and 2300 kW [33]. When it looked at the characteristic specifications of considered WECSs given in Table 3, 2300 kW has the biggest rotor diameter and swept area. By these design configurations, it can be thought that this WECS can produce more wind energy than the other WECSs. But the cut-in speed of 2300 kW WECS is quite greater than the other WECSs. If the average wind speed of the region is not adequate, this WECS cannot produce energy efficiently. The power curves of all wind turbines were given in Fig. 3.

Table 3
Characteristics of wind turbines considered [33].

Rated power (kW)	300	600	1300	2300
Hub height (m)	30	40	60	80
Rotor diameter (m)	33	44	62	90
Swept area (m^2)	875	1520	2830	6362
Cut-in speed (m/s)	3	3	3	4
Rated wind speed (m/s)	15	15	15	13
Cut-off speed (m/s)	25	25	25	25

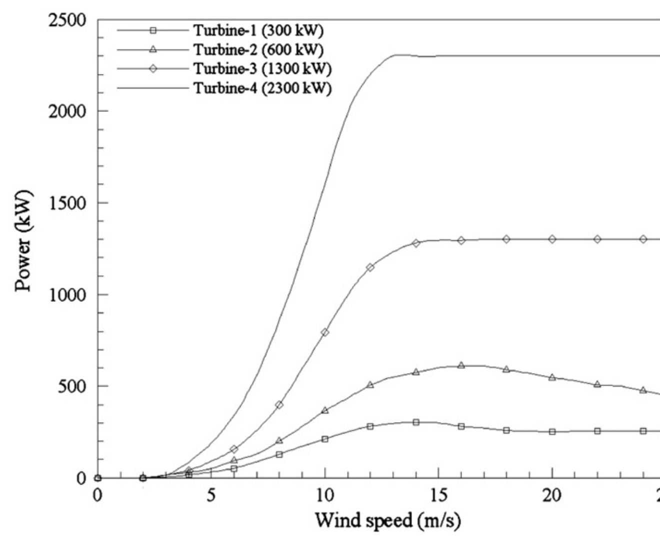

Fig. 3. Power curve of the wind turbines considered [33].

Annual electricity productions (E_w) for considered locations were calculated by using an algebraic equation given in Eq. (2) [33]. Eq. (2) can be obtained from power curve of a wind turbine using curve fitting method and it is used to predict the wind energy production from WECS at each values of wind speed between cut-in and cut-off speeds.

$$P_i(v) = \begin{cases} 0, & v < v_{ci} \\ (a_n v^n + a_{n-1} v^{n-1} + \cdots + a_1 v + a_o), & v_{ci} \le v < v_R \\ P_R, & v_R \le v < v_{co} \text{ or} \\ (a_n v^n + a_{n-1} v^{n-1} + \cdots + a_1 v + a_0), & v_{ci} \le v < v_R \\ 0, & v \ge v_{co} \end{cases} \tag{2}$$

where P_R is rated power of the wind turbine, a is regression constants, v is wind speed, v_{co} is cut-out speed, v_{ci} is cut-in speed and v_R is rated wind speed.

According to annual wind energy output produced from WECSs, capacity factors (C_f) which can help predict performance of WECSs is the ratio of annual produced energy from wind turbine (E_P) and annual rated power (E_R) (rated power of wind turbine × 8760) using following expression:

$$C_f = \frac{E_P}{E_R} \tag{3}$$

5.2. Electrolyzer system

The amount of hydrogen production is related to electrolyzer rated power. If the rated power of electrolyzer increases, the

Table 4
Annual produced electricity, capacity factors and levelized cost of electricity for considered locations at different hub heights [33].

WECS	Turbine-1 (300 kW)			Turbine-2 (600 kW)		
Hub height (m)	**50**	**80**	**100**	**50**	**80**	**100**
Pinarbasi						
E_{wt} (kWh/year)	441515	560086	620075	678387	832002	906448
C_f	0.17	0.21	0.24	0.13	0.16	0.17
C_{elc} ($/kWh)	0.13	0.10	0.09	0.17	0.14	0.13
Sinop						
E_{wt} (kWh/year)	330707	447390	507447	536381	710666	799973
C_f	0.13	0.17	0.19	0.10	0.14	0.15
C_{elc} ($/kWh)	0.17	0.13	0.11	0.22	0.16	0.14
Kirsehir						
E_{wt} (kWh/year)	131787	176618	200303	235101	303945	339734
C_f	0.05	0.07	0.08	0.04	0.06	0.06
C_{elc} ($/kWh)	0.44	0.33	0.29	0.49	0.39	0.34
Nigde						
E_{wt} (kWh/year)	117737	159872	182154	219260	286161	320636
C_f	0.04	0.06	0.07	0.04	0.05	0.06
C_{elc} ($/kWh)	0.49	0.36	0.32	0.53	0.40	0.36
Develi						
E_{wt} (kWh/year)	146338	198443	226924	248777	311527	346087
C_f	0.06	0.08	0.09	0.05	0.06	0.07
C_{elc} ($/kWh)	0.39	0.29	0.25	0.46	0.37	0.33
WECS	**Turbine-3 (1300 kW)**			**Turbine-4 (2300 kW)**		
Hub height (m)	**50**	**80**	**100**	**50**	**80**	**100**
Pinarbasi						
E_{wt} (kWh/year)	1347479	1733873	1931328	2775982	3628222	4058143
C_f	0.12	0.15	0.17	0.14	0.18	0.20
C_{elc} ($/kWh)	0.19	0.14	0.13	0.16	0.12	0.11
Sinop						
E_{wt} (kWh/year)	997194	1387077	1595469	2046408	2886966	3330763
C_f	0.09	0.12	0.14	0.10	0.14	0.17
C_{elc} ($/kWh)	0.25	0.18	0.16	0.22	0.15	0.13
Kirsehir						
E_{wt} (kWh/year)	391615	522453	593292	698218	992149	1153126
C_f	0.03	0.05	0.05	0.03	0.05	0.06
C_{elc} ($/kWh)	0.64	0.48	0.42	0.63	0.44	0.38
Nigde						
E_{wt} (kWh/year)	358206	481710	547622	565673	839912	991640
C_f	0.03	0.04	0.05	0.03	0.04	0.05
C_{elc} ($/kWh)	0.69	0.52	0.46	0.78	0.52	0.44
Develi						
E_{wt} (kWh/year)	424690	565792	641770	688535	1005863	1185565
C_f	0.04	0.05	0.06	0.03	0.05	0.06
C_{elc} ($/kWh)	0.59	0.44	0.39	0.64	0.44	0.37

quantity of hydrogen production increases. However, instead of using a high power electrolyzer, a system including lower power electrolyzers can be used and at lower wind speeds lower power electrolyzer produce the hydrogen, consequently more hydrogen can be obtained than high power electrolyzers. For instance, an electrolyzer with 40 kW rated power needs more energy than the electrolyzer with 10 kW rated power. If the average value of electricity from wind turbine is about 10 kW, electrolyzer with 10 kW rated power will be able to produce more hydrogen than the electrolyzer with 40 kW rated power. In order to produce more hydrogen, it can be used 4 units of 10 kW power electrolyzers. With this consideration, three scenarios were considered in this study:

Scenario-I: 40 kW rated power electrolyzer (total 1 unit).
Scenario-II: 20 kW+10 kW+(5 kW × 2 units) rated powers electrolyzers (total 4 units).
Scenario-III: 10 kW+8 kW+(5 kW × 4 units)+(1 kW × 2 units) rated powers of electrolyzers (total 8 units).

6. Cost analysis

In order to build a renewable energy system, it is necessary to make cost analysis. Due to the fact that renewable energy is a new energy source the costs are quite high. In this study, levelized cost of electricity (LCE) method was used to predict the costs of energy [33] and hydrogen. LCE is very detailed and useful analytical cost analysis method which predicts costs by taking into account of system life, escalation ratio and discount rate.

For a wind energy system, LCE method can be used by dividing total annualized costs of the system elements such as wind turbine, battery bank, inverter and miscellaneous equipment to total annual produced electricity from wind energy system. LCE

Table 5
Hydrogen production quantities and hydrogen production costs at different hub heights for considered locations (Scenario-I).

Scenario-I	PINARBASI		DEVELI		KIRSEHIR		SINOP		NIGDE	
	H_2 (kg/year)	Cost ($/kg$H_2$)	H_2 (kg/year)	Cost ($/kg$H_2$)	H_2 (kg/year)	Cost ($/kWh)	H_2 (kg/year)	Cost ($/kWh)	H_2 (kg/year)	Cost ($/kg$H_2$)
50 m										
300 kW	2656.74	11.31	614.76	43.42	661.19	44.82	2161.04	14.93	469.49	56.27
600 kW	4080.96	11.44	1624.89	35.75	1612.92	34.51	3472.93	14.91	1228.78	39.19
1300 kW	5566.58	10.58	3378.59	35.15	2943.53	38.40	4691.98	14.66	2836.45	41.34
2300 kW	5071.62	5.50	2650	37.42	2436.59	37.06	4255.43	10.10	2152.8	46.17
80 m										
300 kW	3276.75	8.56	978.68	29.27	1019.87	31.14	2886.62	10.99	726.34	38.19
600 kW	4741.40	9.20	2084.66	25.92	2146.81	26.87	4069.73	10.82	1825.57	28.46
1300 kW	5907.28	7.12	4156.59	26.17	3457.96	28.86	5165.97	9.93	3484.16	31.11
2300 kW	5566.58	1.82	3378.59	25.03	2943.53	25.21	4791.57	4.47	2836.45	30.15
100 m										
300 kW	3568.03	7.61	1099.24	25.37	1195.83	26.87	3192.13	9.37	868.61	32.74
600 kW	4987.75	8.43	2370.70	22.94	2381.93	23.48	4313.08	9.40	2080.91	25.32
1300 kW	6030.08	6.20	4576.66	23.10	3678.85	25.27	5334.45	8.39	3782.19	27.48
2300 kW	5746.29	0.53	3764.97	20.62	3194.38	21.31	4995.99	2.48	3167.42	23.69

Table 6
Hydrogen production quantities and hydrogen production costs at different hub heights for considered locations (Scenario-II).

Scenario-II	PINARBASI		DEVELI		KIRSEHIR		SINOP		NIGDE	
	H_2 (kg/year)	Cost ($/kg$H_2$)	H_2 (kg/year)	Cost ($/kg$H_2$)	H_2 (kg/year)	Cost ($/kWh)	H_2 (kg/year)	Cost ($/kWh)	H_2 (kg/year)	Cost ($/kg$H_2$)
50 m										
300 kW	4236.06	9.91	2063.69	31.37	1873.03	34.17	2063.69	19.62	1665.24	39.69
600 kW	5482.99	10.73	3219.47	29.58	3077	31.68	4711.73	14.09	3030.20	34.62
1300 kW	5959.79	9.62	4356.05	34.41	3574.96	37.59	5145.47	13.82	3654.24	40.43
2300 kW	5071.62	2.75	2650	36.27	2436.59	35.76	4255.43	7.72	2152.8	45.03
80 m										
300 kW	4760.6	7.57	2378.56	22.66	2349.45	25.25	2640.64	14.11	2169.93	28.54
600 kW	5826.6	8.56	3721.07	23.86	3562.32	25.09	5141.45	10.09	3654.61	25.96
1300 kW	6195.10	5.89	5044.76	25.60	4057.65	28.13	5507.98	8.84	4290.62	30.39
2300 kW	5566.58	−0.44	3378.59	23.67	2943.53	23.63	4791.57	1.41	2836.45	28.83
100 m										
300 kW	4973.16	6.743	2564.73	19.69	2554.90	22.18	2852.08	12.21	2405.61	25.10
600 kW	5951.46	7.785	4028.83	21.27	3774.14	22.01	5305.24	8.68	3932.51	23.32
1300 kW	6273.35	4.829	5295.23	22.56	4261.42	24.55	5641.74	7.15	4577.79	26.81
2300 kW	5746.29	−2.03	3764.97	19.16	3194.38	19.59	4995.99	−0.92	3167.42	23.69

Table 7
Hydrogen production quantities and hydrogen production costs at different hub heights for considered locations (Scenario-III).

Scenario-III	PINARBASI		DEVELI		KIRSEHIR		SINOP		NIGDE	
	H_2 (kg/year)	Cost ($/kg$H_2$)	H_2 (kg/year)	Cost ($/kg$H_2$)	H_2 (kg/year)	Cost ($/kWh)	H_2 (kg/year)	Cost ($/kWh)	H_2 (kg/year)	Cost ($/kg$H_2$)
50 m										
300 kW	4377.46	9.80	2127.09	25.46	2014.17	33.32	2227.24	18.82	1826.77	38.68
600 kW	5569.33	10.66	3574.32	31.40	3174.87	31.15	4791.10	13.98	3156.77	33.80
1300 kW	5983.34	9.63	4405	34.29	3616.08	37.49	5177.40	13.82	3712.7	40.28
2300 kW	5071.62	2.75	2650	36.27	2436.59	35.76	4255.43	7.72	2152.8	45.03
80 m										
300 kW	4883.80	7.50	2675.37	22.31	2488.95	24.67	2812.49	13.76	2341.53	27.85
600 kW	5890.02	8.53	4126.19	24.99	3659.47	24.79	5208.44	10.04	3783.25	25.52
1300 kW	6214.25	5.90	5059.73	25.49	4104.82	28.08	5531.38	8.85	4360.52	30.32
2300 kW	5566.58	−1.51	3378.58	23.67	2943.53	23.63	4791.57	1.41	2836.45	28.83
100 m										
300 kW	5085.17	6.67	2919.32	19.20	2699.76	21.68	3069.55	11.72	2586.73	24.48
600 kW	6008.53	7.76	4425.25	22.21	3862.66	21.74	5364.14	8.64	4050.54	22.92
1300 kW	6288.59	4.84	5348.80	22.53	4299.72	24.50	5659.31	7.16	4631.19	26.74
2300 kW	5746.29	−3.10	3764.96	19.16	3194.38	19.59	4995.99	−0.92	3167.42	23.69

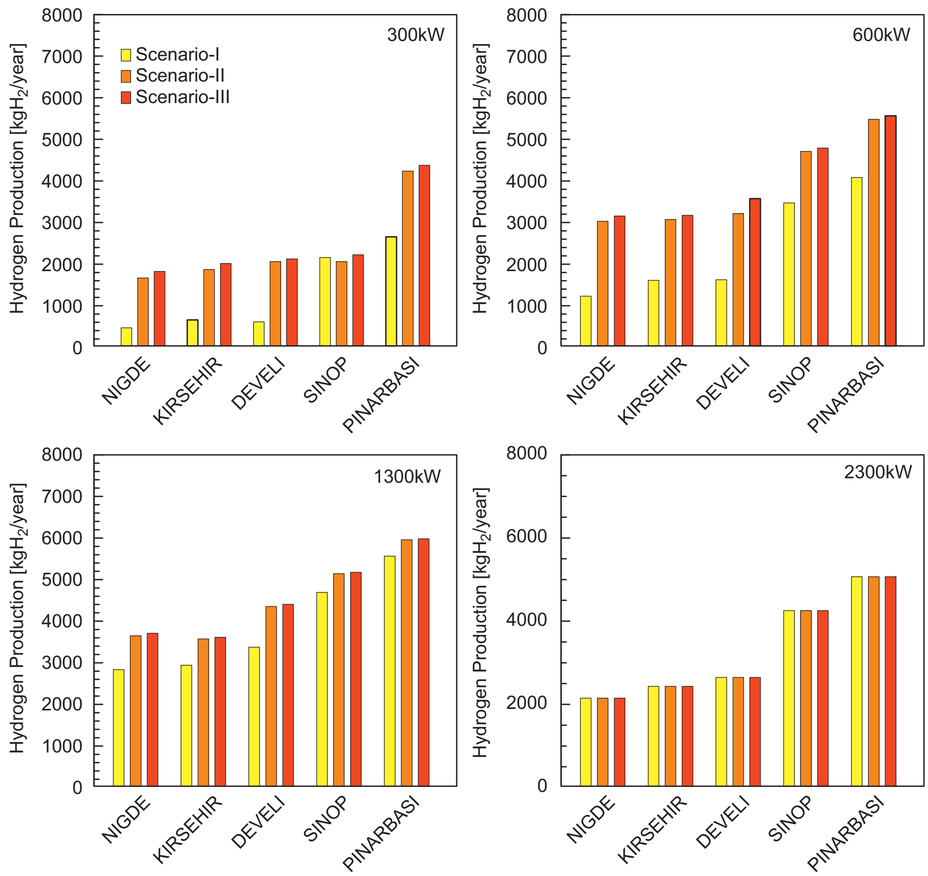

Fig. 4. Comparison of hydrogen productions for four wind turbines for all considered locations at 50 m hub height.

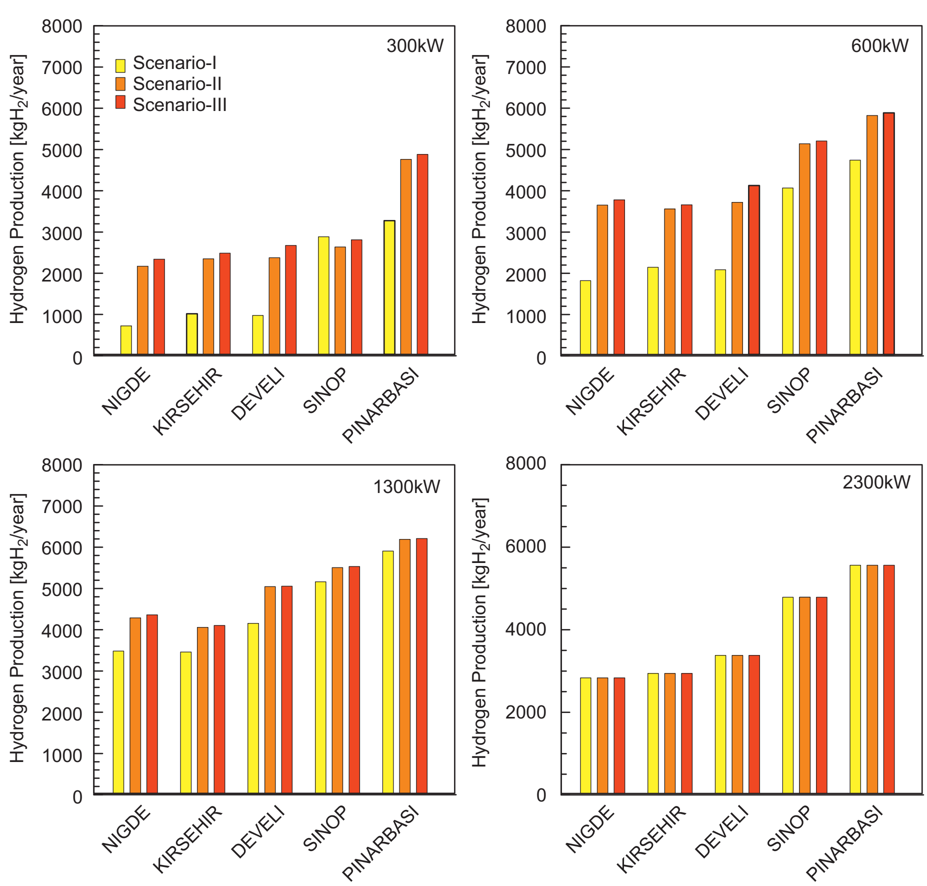

Fig. 5. Comparison of hydrogen productions for four wind turbines for all considered locations at 80 m hub height.

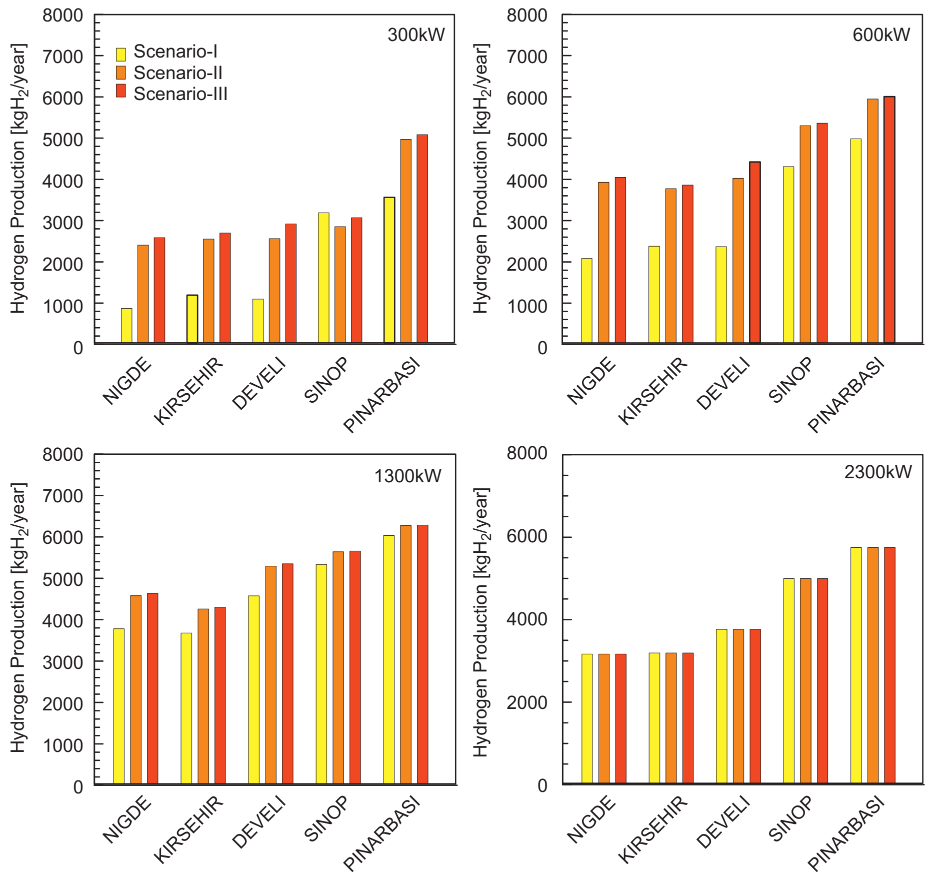

Fig. 6. Comparison of hydrogen productions for four wind turbines for all considered locations at 100 m hub height.

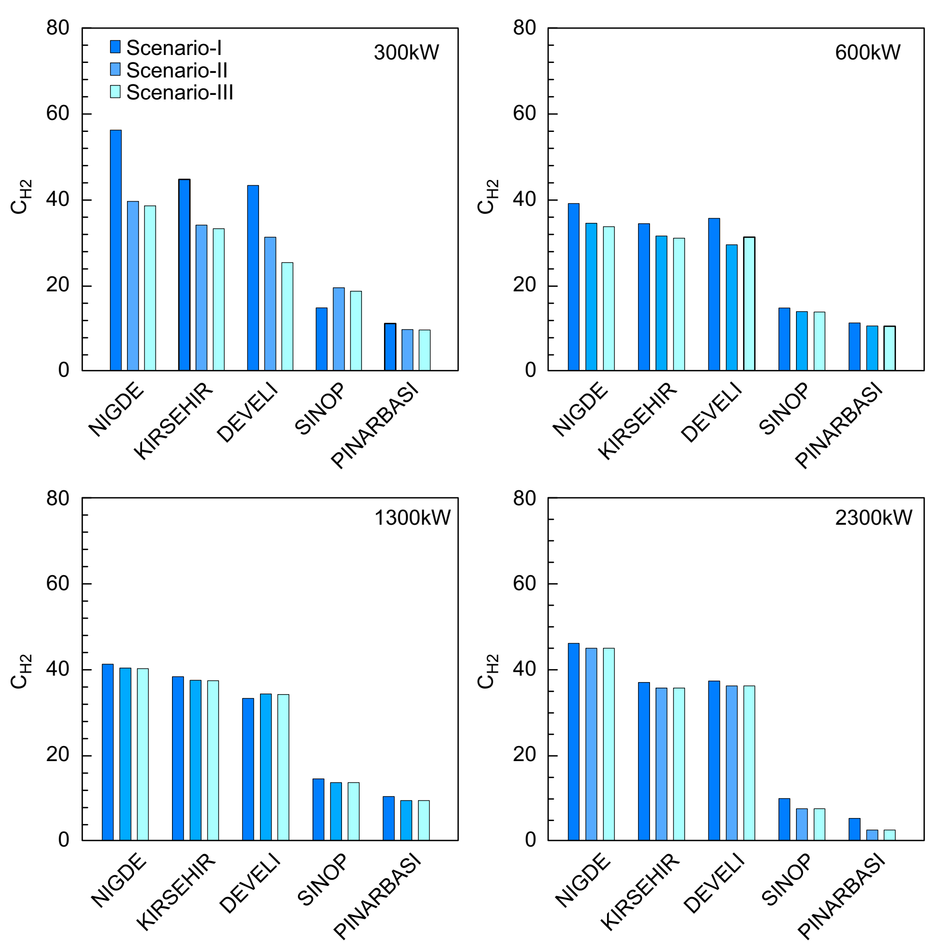

Fig. 7. Comparison of hydrogen production costs for all considered wind turbines for all considered locations at 50 m hub height.

method for wind energy system can be described as given,

$$LCE = \frac{C_{wt}CRF_{wt} + C_{bb}CRF_{bb} + C_{ci}CRF_{ci} + C_{in}CRF_{in} + C_{misc}CRF_{misc} + C_{om}}{E_P} \times [\$/kWh] \quad (4)$$

where C_{wt}, C_{bb}, C_{ci}, C_{in}, C_{misc} and C_{om} are the costs of wind turbine, battery bank, civil costs, inverter and miscellaneous equipment, respectively. The value of costs are multiplied by capital recovery factor (CRF) which is expressed as

$$CRF = \frac{(1+r)^n r}{(1+r)^n - 1} \quad (5)$$

where r and n are discount rate and useful system life, respectively. Total investment costs are quite important and should be taken into account in cost analysis. For a wind energy system, total investment cost is the total of wind turbine cost, battery bank cost, civil costs, inverter and miscellaneous equipment costs. In other words, the total investment cost of a wind energy system (C_w) can be defined by multiplying specific cost of wind energy system (I_w) and rated power of the wind turbine (P_R). The expression can be described as

$$C_w = I_w P_R \quad (6)$$

I_w parameter is related to rated power of wind turbine. While rated power of turbine increases I_w parameter decreases. Between 10 kW and 20 kW rated power turbines called as small size and these turbines specific costs have a range from 2200 $/kW to 2900 $/kW. Greater than 20 kW and less than 200 kW rated power turbines called medium size and they have a range from 1500 $/kW to 2300 $/kW. Greater than 200 kW rated power turbines called large size and their specific costs are between 1000 $/kW and 1600 $/kW [49].

LCE method includes the costs of operation and maintenance for wind energy system. The operation and maintenance costs increase when the system life increases. So it should be escalated by using given expression:

$$C_{om-esc} = \frac{C_{om}}{r - e_{om}} \left[1 - (1+e_{om})^n (1+r)^{-n}\right] \ [\$/year] \quad (7)$$

where $C_{om\text{-}esc}$ is the operation and maintenance cost and e_{om} is the escalation ratio.

In this study, system life, n was assumed as 25 years, discount rate, r was assumed as 12%, operation and maintenance cost, C_{om} was assumed as 15% [50], lifetime of battery bank was considered as 7 years [50], lifetime of inverter was taken as 10 years [50], escalation ratio was taken as 3.5% [51] and specific turbine cost was taken as 1000 $/kW.

Hydrogen cost can be calculated by considering annual capital cost of the electrolyzer, annual cost of energy which consumes by electrolyzer using wind energy, operation and maintenance costs of electrolyzer, cost of exported energy to grid and annual produced hydrogen. In order to annualize the costs of electrolyzer and exported energy, these values need to be multiplied by CRF. Levelized hydrogen cost, in $/kgH$_2$ unit, can be expressed as:

$$C_{H_2} = \frac{C_{EACC}CRF_{EACC} + C_{EE} + C_{OM-EE} - C_{EXP}CRF_{EXP}}{m_{H_2}} \ [\$/kgH_2] \quad (8)$$

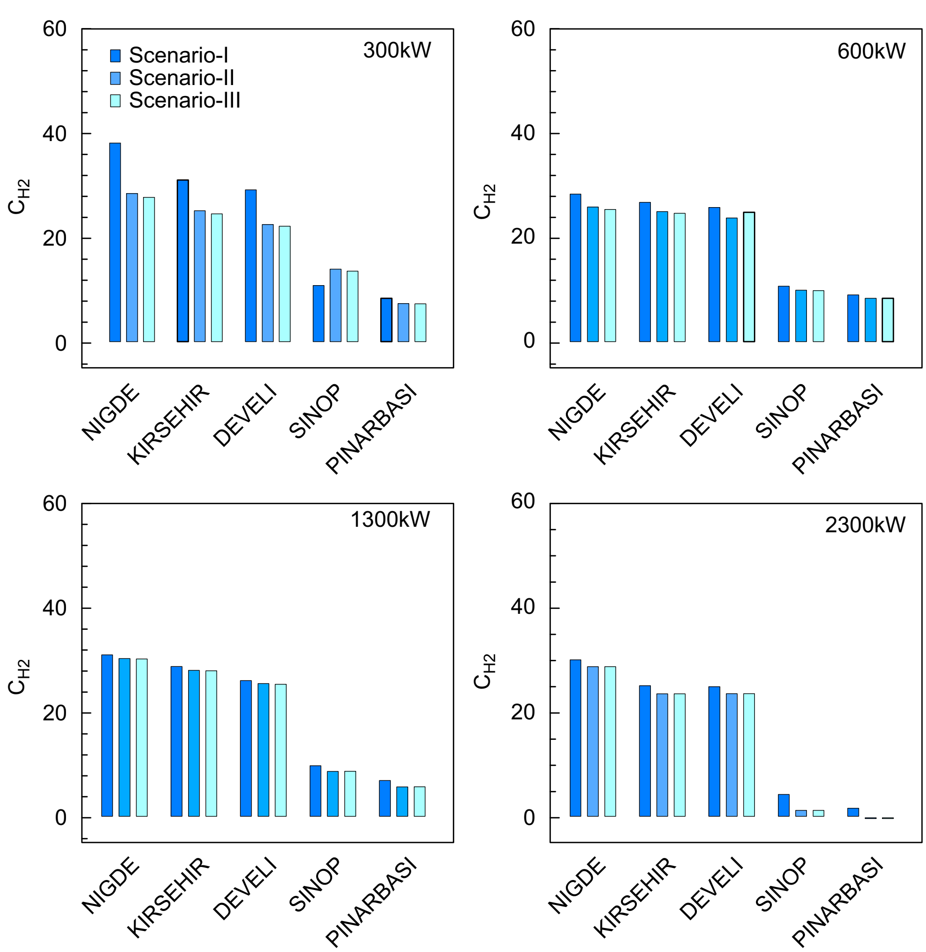

Fig. 8. Comparison of hydrogen production costs for all considered wind turbines for all considered locations at 80 m hub height.

where C_{H_2} is levelized cost of hydrogen and m_{H_2} is annual produced hydrogen from electrolyzer. In order to calculate the cost of hydrogen, followed assumptions were considered:

- Specific cost of electrolyzer was 1000 $/kWh.
- Discount rate was 12%.
- Service lifespan of the electrolyzer system was 10 years.
- Escalation ratio of the electrolyzer system was 2%.

Energy exported to grid, C_{EXP} must be subtracted from the other cost values, because it provides income to system. When calculating the C_{EXP}, following equation can be used as:

$$C_{EXP} = E_{EXC} C_{GRID} \mathrm{CRF}_{EXP} \tag{9}$$

where E_{EXC} is excess energy from the electrolyzer, C_{GRID} is the price of energy sold to the grid. C_{GRID} was taken as 0.069$ according to renewable energy law in Turkey in 2005 [52]. Furthermore, CRF_{EXP} was used to annualize the cost of energy exported to grid.

7. Results and discussions

7.1. Energy output and energy cost

The electricity production from wind turbines, capacity factors of WECSs and LCE were calculated and given in Table 4 [33]. As can be seen in Table 4, the maximum energy obtained from Pinarbasi. For this location, annual electricity production was 4058.1 MWh/year at hub height of 100 m from wind turbine with 2300 kW rated power. Sinop follows Pinarbasi with 3330.7 MWh/year from wind turbine enjoying 2300 kW rated power at 100 m hub height. The minimum energy production occurred in Nigde with 300 kW rated power at 50 m hub height. For this location, E_{wt} value was calculated as 117.7 MWh/year. Because of its lowest electricity production, its capacity factor value has quite low level. The maximum value of capacity factor was calculated as 20% from wind turbine with 2300 kW at 100 m hub height in Pinarbasi.

The costs of electricity production are quite important; the costs directly affect the hydrogen production costs, because the produced energy is used to produce hydrogen from electrolyzers. It can be seen from Table 4 that the wind turbine with 300 kW rated power at 100 m hub height has the minimum energy cost as 0.09 $/kWh in Pinarbasi. The maximum value of 0.78 $/kWh was obtained from wind turbine with 2300 kW rated power at 50 m hub height in Nigde.

7.2. Hydrogen production and hydrogen cost

As mentioned before, three scenarios were considered and made calculations for each scenario to obtain effective hydrogen production from electrolyzers.

7.2.1. Scenario-I

In this scenario, it was considered that there was one electrolyzer with 40 kW rated power. Amounts of hydrogen production and hydrogen production costs were computed using this one electrolyzer for each considered locations at three different hub heights. As seen from Table 5, while rated power of the wind turbine increases, hydrogen production increases and hydrogen

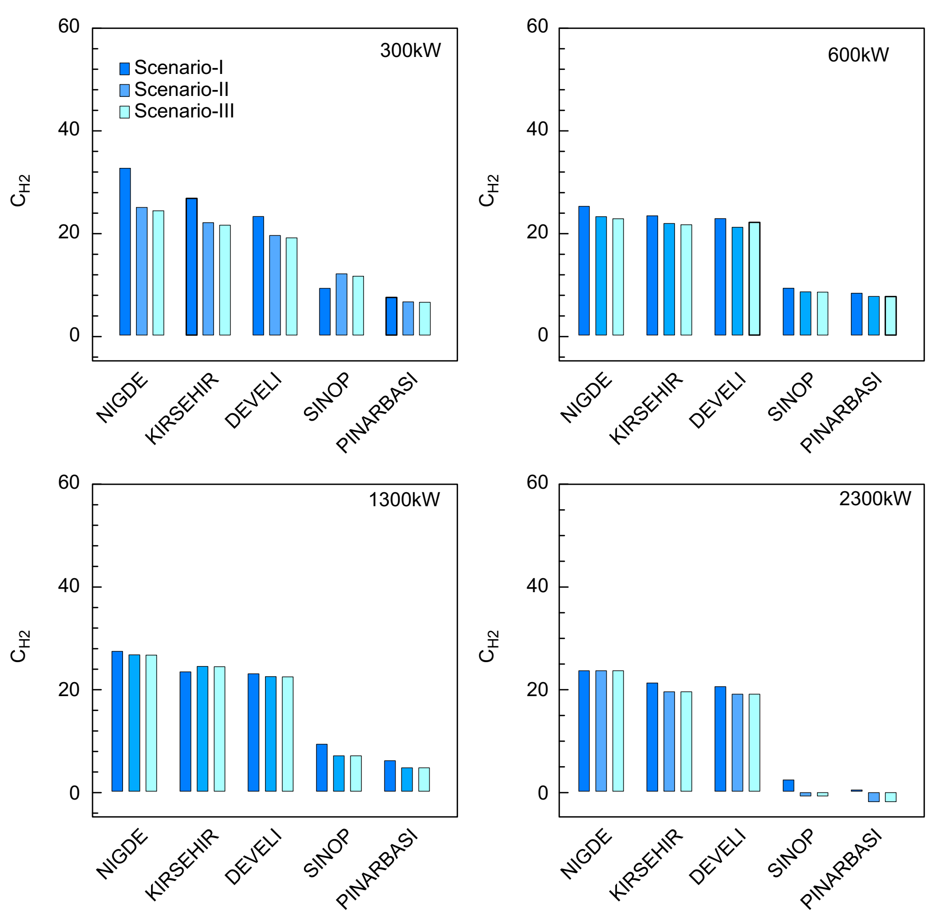

Fig. 9. Comparison of hydrogen production costs for all considered wind turbines for all considered locations at 100 m hub height.

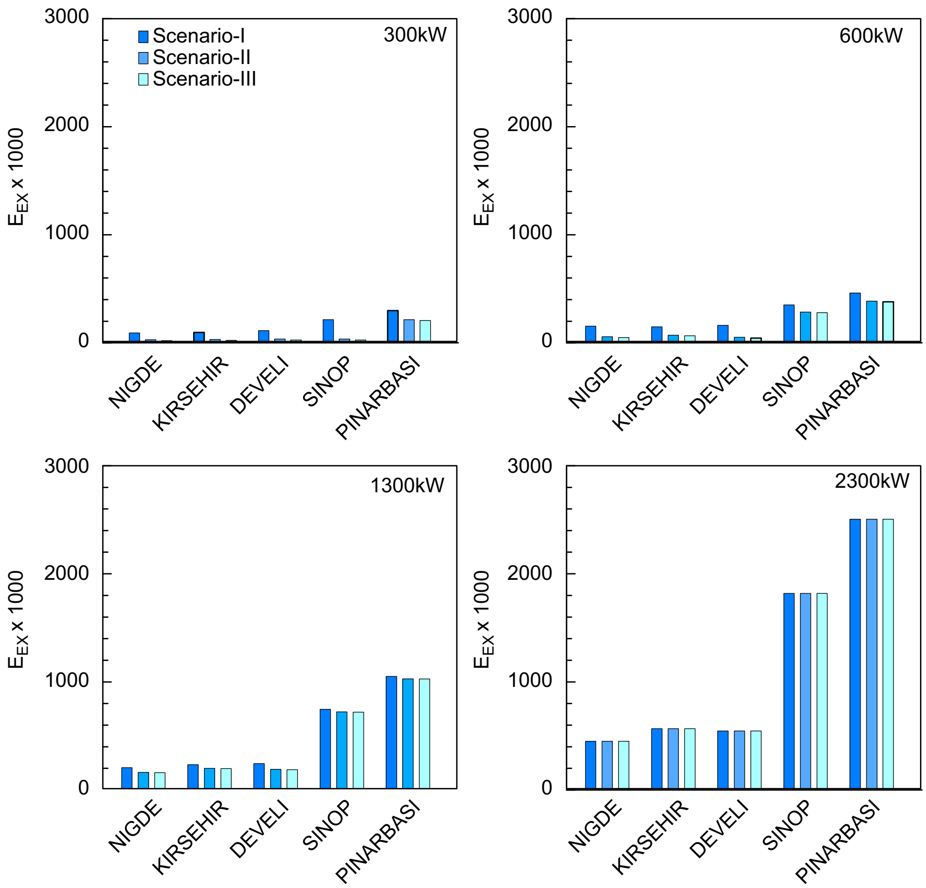

Fig. 10. Comparison of excess energies for four wind turbines for all considered locations at 50 m hub height.

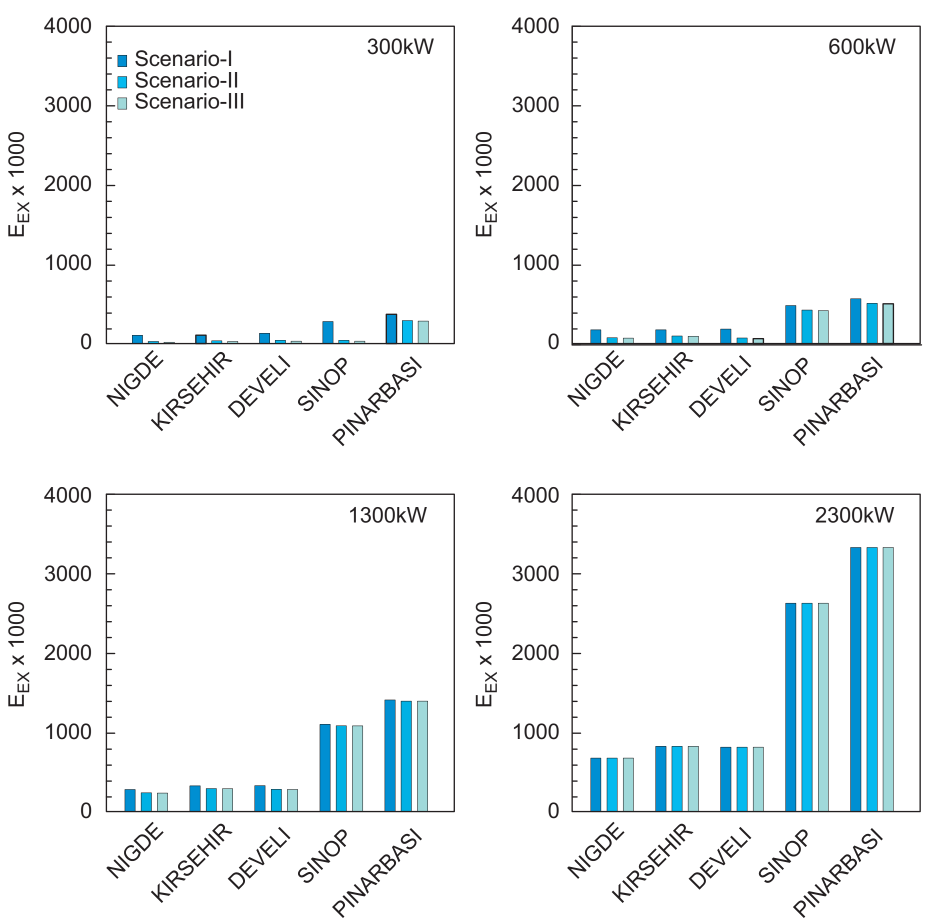

Fig. 11. Comparison of excess energies for four wind turbines for all considered locations at 80 m hub height.

production costs decrease. The maximum value of hydrogen production was found as 6030.08 kgH_2/year from wind turbine with 1300 kW rated power at 100 m hub height in Pinarbasi. Because of high amount of hydrogen production, it has minimum hydrogen production cost of 0.53 \$/kgH_2.The important point in Table 5 is hydrogen production from wind turbine with 1300 kW rated power is greater than wind turbine with 2300 kW rated power for all hub heights, but hydrogen production costs are less than rated power of 2300 kW wind turbine. The reason for this was electricity production from wind turbine with 2300 kW rated power was greater than 1300 kW, so when the excess energy from 2300 kW wind turbine sold to the network the costs decrease more than 1300 kW wind turbine.

7.2.2. Scenario-II

In this scenario, 4 units electrolyzers (20 kW+10 kW+ (2 × 5 kW)) were taken into account to produce more hydrogen than Scenario-I. In Table 6, the hydrogen production in Scenario-II was greater than Scenario-I. In Scenario-I, the rated power of electrolyzers can produce more hydrogen than Scenario-I due to their low rated powers. From Table 6, it can be seen that hydrogen production from 1300 kW wind turbine was greater than 2300 kW wind turbine. The reason for this was 2300 kW wind turbine did not start producing hydrogen until wind speed was 4 m/s. It means hydrogen production range from wind turbine with 2300 kW was less than 1300 kW.

In Pinarbasi and Sinop with 2300 kW wind turbine, hydrogen production costs were less than zero at 100 m hub height. It means when plant used the 2300 kW wind turbine at 100 m hub height in these locations, it would be more profitable.

7.2.3. Scenario-III

In this scenario, the rated powers of electrolyzers were chosen less than the other scenarios. 8 units of electrolyzers (10 kW+8 kW+(4 × 5 kW)+(2 × 1 kW)) were considered to produce hydrogen. As can be seen in Table 7, hydrogen productions were the greatest value in all scenarios considered. The maximum hydrogen production was 6288.59 kgH_2/year at 100 m in Pinarbasi with 1300 kW wind turbine whereas minimum hydrogen production was 1826.77 kgH_2/year at 80 m in Kirsehir with 300 kW wind turbine. While the maximum hydrogen production cost was obtained as 38.68 \$/kgH_2 from wind turbine with 300 kW rated power at 50 m hub height in Nigde, the minimum hydrogen production cost was −3.1 \$/kgH_2 with 2300 kW wind turbine at 100 m hub height in Pinarbasi.

Comparisons of hydrogen productions for four wind turbines for all considered locations at different hub heights were given in Figs. 4–6. These figures points that hydrogen production levels increase by increasing rated power of wind turbine and increasing hub height. In Scenario-III, quantity of hydrogen production was greater than the other scenarios because of low rated power electrolyzers. Note that, from 2300 kW wind turbine hydrogen production quantities were the same in all scenarios, because in this situation electrolyzers worked with full capacity in three scenarios. As mentioned before, in this situation hydrogen production amounts were less than other wind turbines, because 2300 kW wind turbine did not work under 4 m/s wind speed.

Hydrogen production costs for all considered wind turbines for all locations at 50 m, 80 m and 100 m hub height were compared in Figs. 7–9. As shown in Figs. 7–9, hydrogen production costs decrease by increasing rated power of wind turbine and increasing hub height. Furthermore, hydrogen production costs have the

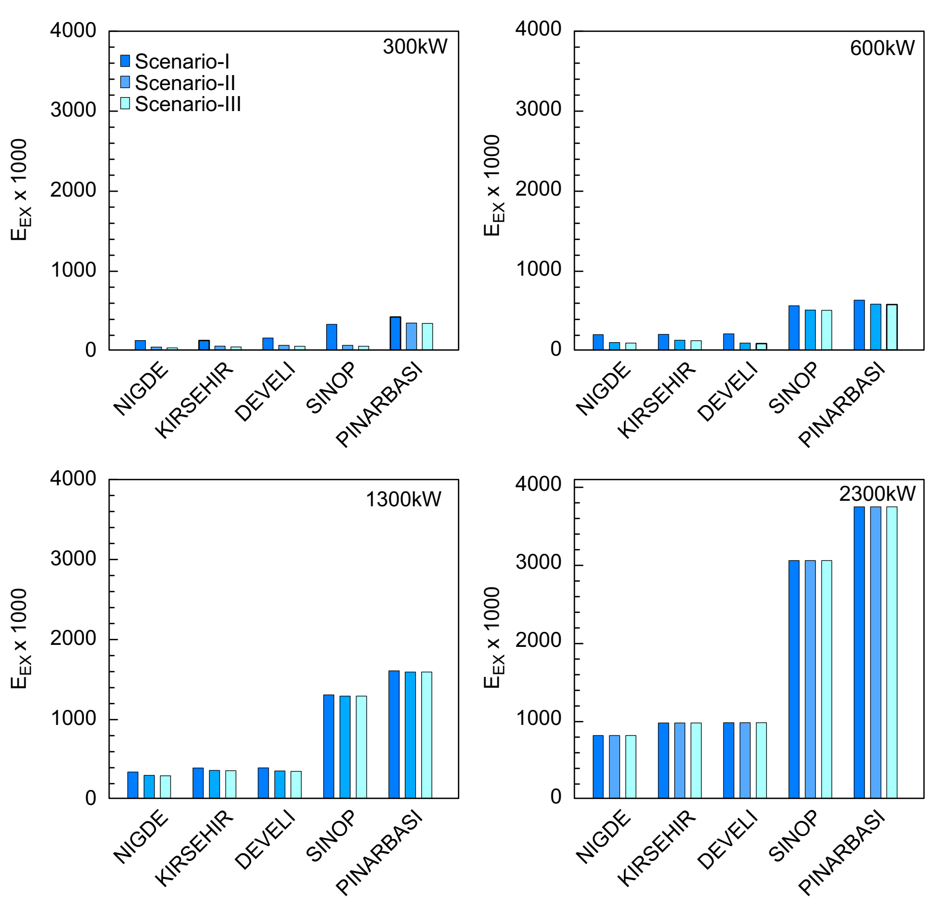

Fig. 12. Comparison of excess energies for four wind turbines for all considered locations at 100 m hub height.

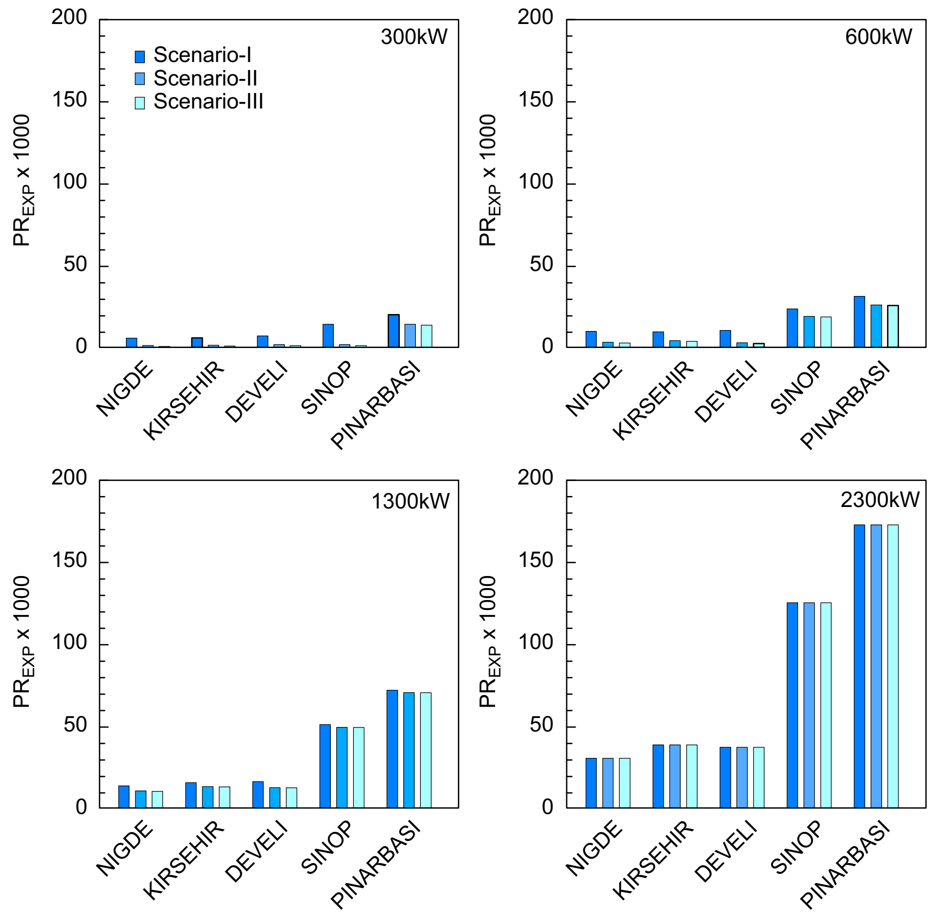

Fig. 13. Comparison of PR_{EXP} for four wind turbines for all considered locations at 50 m hub height.

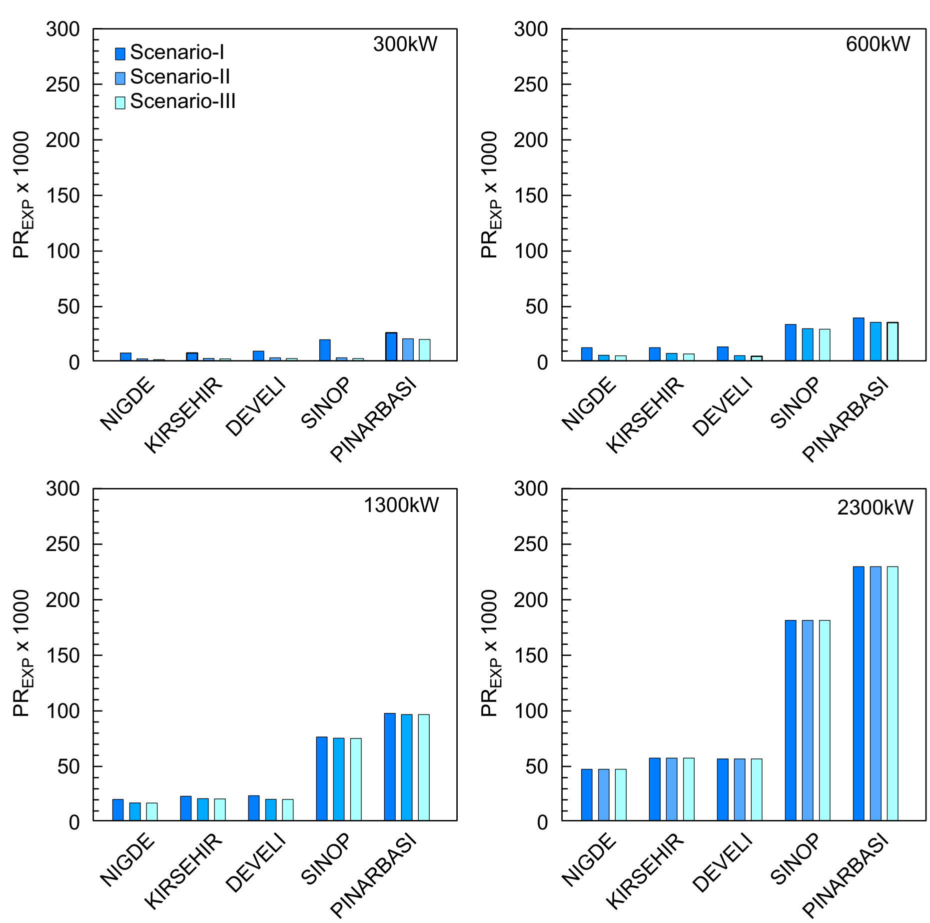

Fig. 14. Comparison of PR_{EXP} for four wind turbines for all considered locations at 80 m hub height.

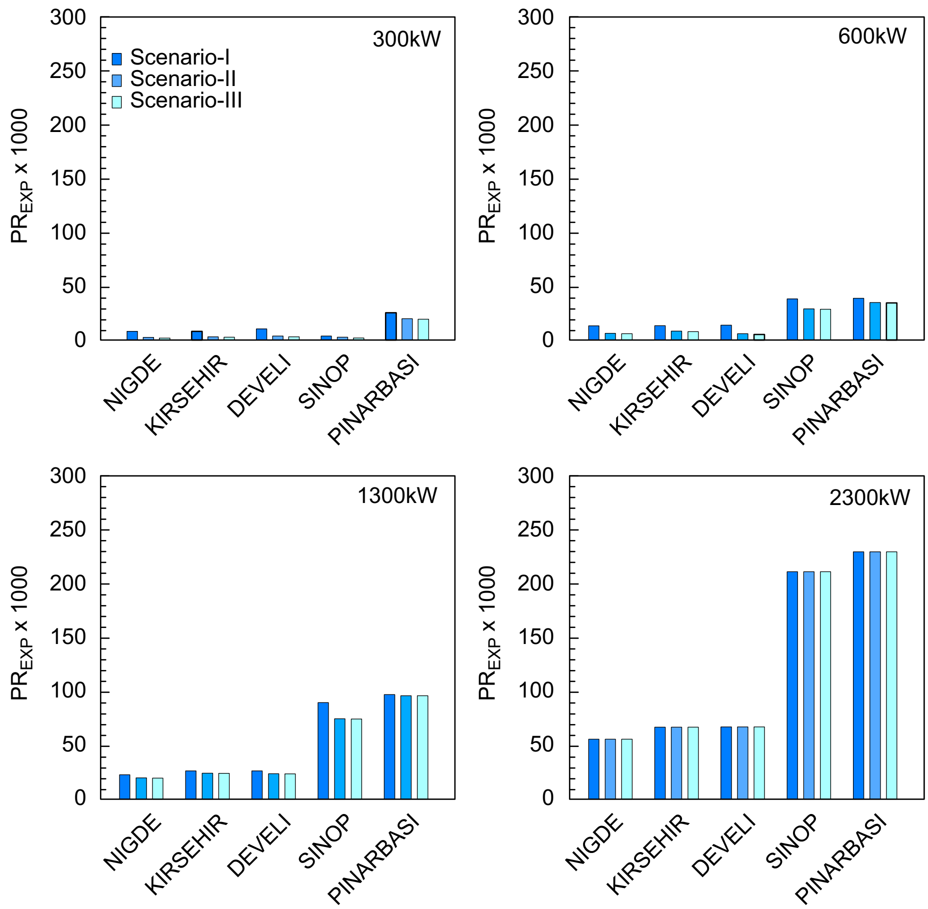

Fig. 15. Comparison of PR_{EXP} for four wind turbines for all considered locations at 100 m hub height.

lowest value at Scenario-III because of low rated powers of electrolyzers. In Figs. 8 and 9, hydrogen production costs are under zero. The amounts of excess energy in Pinarbasi with 2300 kW wind turbine at 100 hub height were greater than other locations. Due to selling these excess energies to the network, costs were reduced.

In Figs. 10–12, excess energy quantities were shown, and in Scenario-I excess energy amounts were higher or equal to the other scenarios. The reason for this was that 40 kW electrolyzer did not produce hydrogen at low wind energies. Therefore, those low wind energies were assumed as excess energy. Furthermore, in Sinop and Pinarbasi locations, especially with 2300 kW wind turbine, excess energies were higher than the other locations. Because of higher wind potential of Sinop and Pinarbasi, high wind energy can be produced from wind turbine. Hence, it can be sold more energy to the network in these locations.

The profit from energy exported to the grid (PR_{EXP}) was calculated for each locations and scenarios. The PR_{EXP} was directly proportional to the excess energy. While excess energy increases, PR_{EXP} increases. Furthermore, hydrogen production costs decrease while excess energy increases. The variation of PR_{EXP} according to scenarios and locations were given in Figs. 13–15. As can be seen in Figs. 13–15, PR_{EXP} values were directly proportional to the wind turbines and hub heights. While hub height increases PR_{EXP} increases, rated power of wind turbine increases PR_{EXP} increases. Similarly with Figs. 10–12, in Sinop and Pinarbasi PR_{EXP} was higher than the other locations. While the maximum value of PR_{EXP} was 211,407.9 \$/year in Pinarbasi with 2300 kW wind turbine at 100 m hub height, the minimum value of PR_{EXP} was 206,72.08 \$/year with 300 kW wind turbine at 50 m hub height in Nigde.

8. Conclusion

Due to avoiding of fossil fuels, it is very important to make researches about clean, renewable and alternative energy sources. Renewable and alternative energy sources are the most important key to protect the world on account of the fact that their ability to generate energy without harmful emissions to the environment. Especially in decades, wind and hydrogen energy have been developed more quickly in all renewable energy sources. In this study, hydrogen production potentials and costs were investigated for five different locations in Central Anatolia Turkey. Hydrogen production and production cost variations compared for different scenarios, different wind turbines and different hub heights. For the amounts of hydrogen production, the maximum hydrogen production was 6288.59 kgH_2/year in Pinarbasi with 1300 kW wind turbine at 100 m hub height for Scenario-III. The minimum hydrogen production was 1665.24 kgH_2/year in Nigde with 300 kW wind turbine at 50 m hub height for Scenario-II. According to hydrogen production cost calculations, the minimum hydrogen production cost was -3.1 \$/kgH_2 in Pinarbasi with 2300 kW at 100 m hub height for Scenario-III whereas the maximum hydrogen production cost was 56.27 \$/kgH_2 in Nigde with 300 kW at 50 m hub height for Scenario-I.

Consequently, both utilization of wind energy and hydrogen production using a wind–electrolyzer energy system are considerable

since Pinarbasi and Sinop have remarkable wind potential, and the wind energy conversion and wind–electrolyzer energy systems should be encouraged in Pinarbasi and Sinop.

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